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13. ABSTRACT (*Maximum 200 words*)

The following results were obtained under the contract: numerical acceleration of convergence for the EM algorithm; a characterization of the rank-n ambiguity; a characterization of the phase delay ambignity; determination of the minimal number of known and unknown signals for sensor location observability; a large class of cyclic regression algorithms for multiple signal direction finding; array sensor localization and calibration by cyclic regression; cyclic regression for the weighted subspace fitting for direction finding: cyclic regression for harmonic retrieval from colored noise; a statistical approach to training multilayer perceptrons.

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Final Technical Report
on
Maximizing the Convergence Rate of the EM Algorithm for the Multiple Broad-Band Signal Estimation and Detection
for

Contract Number: N00014-88-K-0490

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Office of Naval Research

Program Manager: James G. Smith
Applied Mathematics and
Computer Science

by

University of Maryland Baltimore County
Baltimore, MD 21228

Principal Investigator: James T. Lo
Department of Mathematics
and Statistics

1. OBJECTIVES

Our goal has been to develop a comprehensive and integrated algorithm of processing sensor array measurements that is ready for implementation on advanced sonar and radar systems. The algorithm should be capable of detecting, localizing, and tracking multiple signal sources with various statistical correlations and frequency band widths in the possible presence of array sensor uncertainties. The algorithm should be robust and proven to use all the information available in an optimal fashion. The following issues have been addressed:

(a) Exploitation of the linearity and separability structures in the log likelihood function for the fast and robust convergence of the EM algorithm and its closely related cyclic regression (CR) method.

(b) Generalization of the EM and the CR Methods to a large class of algorithms, from which an adaptive algorithm can be obtained that has the best performance in all signal/sensor environments.

(c) Determination for the confidence regions of the estimated DOAs of the signals.

(d) I ection of the number of signals with a greater success rate and less extra computation than the standard information-theoretic method.

(e) Self-localization and calibration of the array sensors with or without a priori probability distribution of the locations and phases of the same.

(f) Observability conditions for array sensor self-localization and calibration.

(g) Integration of narrowband algorithms into a parallel algorithm for broadband signals.

(h) Treating the optimal weighted subspace fitting as a weighted least squares estimation.

(i) Extending the CR method to maximum likelihood retrieval of harmonics in colored noise.

(j) Applying the CR techniques developed for array signal processing to training multilayer perceptrons.

2. IMPORTANT ACCOMPLISHMENTS

In order to achieve our ultimate goal stated in 1, we have emphasized both the theoretical development and the computer simulation. All the results to be summarized below have amply been simulated and verified in adverse signal/sensor environments. The details of the results can be found in the publication or presentation indicated at the end of each item. The publications and presentations are listed in the next Section of this report.

(a) Numerical acceleration of convergence:

The EM/CR type of algorithm is a fixed point iteration. Applying the Newton-Raphson method to each of the corresponding fixed point equations, we drastically speeded up the convergence. This idea of numerical acceleration was first published by Steffensen in 1933. There are many generalizations to the multivariable case, which will be worth trying out in future research. [3]

(b) Characterization of the rank-n ambiguity:

When the sensor locations have to be estimated *along with the signal* DOAs, the array manifold is parameterized by the phase differentials. It may intersect the signal subspace at points that represent false action vectors. This phenomenon was called rank-n ambiguity by R.O. Schmidt.

A necessary and sufficient condition for the rank-2 ambiguity is given, whose geometric meaning as well as an example are examined in detail. We also offered a conjecture about the general rank-n amgibuity. Its proof or disproof is an open problem. [4]

(c) Characterization of the phase delay ambiguity:

The phase differentials are taken modulo 2π in the arguments of the action vector components, resulting in the so-called phase delay ambiguity. Geometrically, this translates into an ambiguity concerning the relative distances between the array sensors along each signal DOA. In other words, the relative distances can only be determined modulo an integral multiple of each signal wavelength.

The phase delay ambiguity can be avoided by either starting with very good a priori sensor location estimates or using known and unknown calibrating signals with certain frequency/geometry structure. A necessary and sufficient condition is given for no phase delay ambiguity. [4]

(d) Minimal number of known and unknown signals for sensor location observability:

It was observed by Rockah and Schultheiss that the shape of the sensor array is observable, provided that three signals with unknown but different DOAs are available. Obviously, if there are no known signals in the measurements, a rotation or reflection of the array can not be observed from unknown signals alone, no matter how many. We examined in detail the numbers of known and unknown signals required. The assumptions are made that the phase delays are available without ambiguity and the measurements are noise-free. [4]

(e) A large class of cyclic regression algorithms for multiple signal direction finding:

In each step in the iteration cycle, the standard CR maximizes the log-likelihood function. But in the step of estimating the action vectors, the covariance matrix of the signals needs to be inverted. Since the covariance matrix of coherent signal is not invertible, the standard CR without ridge regression fails to work for coherent signals.

The EM algorithm circumvents this difficulty by evaluating the conditional expectation of the action vectors given the sensor measurements. However, it converges slowly.

Some gradient descent methods were applied to deal with the same difficulty. The performances of the resulting algorithms turned out to be very good for some signal/noise situations and very poor for others.

A close examination of the equations for these algorithms revealed that they all belong to the same class with different values of a class index. The index can be viewed as the proportions of the measurement noise variance they are assigned to each piece of complete data, namely the action vector times the signal waveform.

Five algorithms from the class, each with some intuitive backing, were singled out for simulations study. Results are very interesting and greatly enhance our understanding of the algorithms. Nevertheless, an adaptive algorithm that works best in all situations has yet to be found. More statistical analysis needs to be done. [6]

(f) Array sensor localization and calibration by cyclic regression:

Our method is an extension of the cyclic regression for direction finding. The extension keeps the essential characteristics of cyclic regression, namely the iteration over a finite number of linear regression stepts. In addition to the separability and the linearity structures used for direction finding, the extension is made possible by the property that the sensor coordinates and phases enter the arguments of the complex-valued components of the action vectors in a linear fashion.

A salient feature of our method as opposed to others is that direction finding and sensor localization and calibration can be done at the same time on the same set of measurements, as long as the observability conditions for all the unknown parameters are satisfied. This is important, when the fluctuations of the sensor locations and phases are significant from set to set of measurements. [5]

(g) Integration of the a priori information about the signal DOAs and the sensor locations and intrinsic phases:

Two methods of integrating the a priori information into our maximum likelihood estimation for signal direction finding and sensor self-localization and calibration have been obtained.

If the a priori information is highly unreliable and the observability conditions are satisfied modulo an unknown rotation, we first determine the shape of the sensor array using the sensor measurements only and then rotate the sensor array with the fixed shape to fit the a priori information. An interesting criterion for rotation has been derived.

If the a priori information is reliably described as probability densities and the observability conditions are satisfied (perhaps with the help of the a priori information), the cyclic regression is easily modified to integrate the priori information by augmenting the linear regression equations in each iteration cycle. [6]

(h) In a recent paper, Viberg and Ottersten proposed a weighted subspace fitting (WSF) criterion for direction finding. However their algorithm for WSF involves the computation of the eigenvalues and eigenvectors of the sample covariance matrix and a Gauss-Newton type algorithm. We (P.I., Nagaraj and Rukhin) derived an asymptotically equivalent expression of the WSF criterion which does not involve eigenvalues and eigenvectors. Facilitated with the expression, a CR algorithm was obtained to replace the Gauss-Newton type algorithm for estimating the signal DOAs. [7]

(i) The estimation of the frequencies of sinusoidal components embedded in white or colored noise is one of the fundamental problems encountered in a large range of fields. We succeeded in extending the CR method to evaluating the maximum likelihood estimates of these component frequencies. [8]

(j) Due to their almost unlimited capability to represent nonlinearities, the multilayer perceptrons (MLPs) have found a wide range of applications including signal processing and adaptive control. Finding a fast and accurate method of training an MLP has been a focal point of research in the field of artificial neural networks. At least 10 different training algorithms have been published in the past 5 years.

The application of the CR techniques to the training problem yielded a novel training algorithm, which we call the backestimation algorithm. As opposed to the standard backpropagation of "deltas", which are actually the gradients of the error surface, we backestimate the neuron outputs. More specifically, we compute the probabilistic expectation of the output of a layer conditioned on that of the next layer.

Results of extensive numerical experiments show that both the convergence rate and the accuracy level of backestimation are better than those of backpropagation and its variants by several orders of magnitude. [9]

3. SIGNIFICANCE

If I am asked to summarize all my results in one sentence, I would say that they are simply a very effective decomposition of the nonlinear least-squares estimation problem into linear regressions. The decomposition enables us to handle information from different times, frequencies, and sources in an efficient and integrated manner. Although we have concentrated on the maximum likelihood approach, which is a nonlinear least-squares problem, our results are readily applicable to other least-squares formulations such as the optimal weighted subspace fitting.

(a) The techniques developed for integrating the a priori information in the CR algorithm are of particular importance. They suggest a recursive algorithm for maximum likelihood direction finding in the presence of array sensor uncertainties. A recursive algorithm is desired, if the signal source and/or the array sensors are mobile or if the best possible signl DOA estimates are constantly required. The recursive algorithm updates the estimates for each in-coming snapshot. It should take full advantage of all the current information in terms of the current estimates and their covariances and the newly acquired snapshot. The P.I. is working on such a recursive algorithm.

(b) The discovery of a large class of CR algorithms with specific class index parameters greatly enhanced our understanding of the structures of cyclic regression. It calls for an adaptive way of tuning those index parameters so that the CR algorithm adaptively works best in all signal/sensor environments.

(c) The transformation of Viberg and Ottersten's WSF criterion and the use of a CR algorithm for minimizing it greatly reduce the amount of computation needed to implement the WSF for direction finding.

(d) The CR algorithm for the retrieval of harmonics in colored noise eliminates the following three difficulties associated with existing methods:

(1). White noise assumption: Very often the Nyquist sampling rate disallows sufficient decorrelation between measurements required for the white noise assumption.

(2). Time-aperture reduction: The CR algorithm does not require the estimation of correlations and thus avoids time-aperture reduction.

(3). Excessive computation associated with Gauss-Newton procedure.

(e) The backestimation algorithm for trainin multilayer perceptron has the potential to greatly outperform the standard backpropagation and its variants. It is based on the cyclic regression techniques and thus inherits the versatility of the CR algorithms.

4. FUTURE RESEARCH

Many problems have been resolved during the contract period for developing a comprehensive and integrated array signal processing system based on the CR algorithm. Three major tasks remain to be carried out:

(a) Develop a recursive algorithm for maximum likelihood direction finding in the presence of array sensor uncertainties.

(b) Derive a signal detection scheme that works jointly with the CR algorithm so as to achieve a greater success rate and less extra computation.

(c) Integrate the narrowband CR algorithms into a parallel algorithm for broadband signals.

5. PUBLICATIONS AND PRESENTATIONS

[1] Cyclic Regression for Multiple Signal Estimation via the EM Algorithm, *Proceedings of the 22nd Asilomar Conference on Signals, Systems & Computer*, pp. 603–608, Pacific Grove, California, 1988.

[2] Two Observability Conditions for Array Sensor Localization, *Proceedings of the 1989 Conference on Information Sciences and Systems*, pp. 453–458, Baltimore, Maryland, 1989 (with S. L. Marple, Jr.).

[3] Cyclic Regression for Multiple Signal Direction Finding, submitted for publication.

[4] Observability Conditions for Multiple Signal Direction Finding and Array Sensor Localization, accepted for publication in the *IEEE Transactions on Signal Processing* (with S. L. Marple Jr.).

[5] Array Sensor Localization and Calibration by Cyclic Regression, Proceedings of the 1990 International Conference on Acoustics, Speech and Signal Processing, pp. 2939-2942, Albuquerque, New Mexico, 1990.

[6] A Large Class of Cyclic Regression Algorithms for Multiple Signal Direction Finding, Proceedings of the 1990 Conference on Information Sciences and Systems, pp. 818-823, Princeton, New Jersey, 1990.

[7] Cyclic Regression for Weighted Subspace Fitting to Find Multiple Signal Directions, Proceedings of the Oceans '90 Conference, pp. 518-520, Washington, D.C., September 1990 (with N. K. Nagaraj and A. Rukhin).

[8] Maximum Likelihood Retrieval of Harmonics in Colored Noise by Cyclic Regression, *Proceedings of the Oceans '90 Conference*, pp. 369–373, Washington D.C., September 1990.

[9] Backestimation for Training Multilayer Perceptron, *Proceedings of the 1991 International Conference on Acoustics, Speech and Signal Processing*, pp. 1065–1068, Toronto, Canada, 1991.